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REVIEW ARTICLE

Near Infrared Spectroscopy as a Diagnostic Tool for Screening of Intracranial Hematomas; A Systematic Review and Meta-Analysis

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Abstract: **Introduction:** Evidence supports the clinical applicability of near-infrared spectroscopy (NIRS) in intracranial hematoma detection in prehospital settings. This systematic review and meta-analysis aimed to determine the diagnostic yield of NIRS for detecting intracranial hematoma in traumatic brain injury (TBI) patients. **Methods:** A systematic search was performed in July 2024 in Medline, Embase, Scopus, and Web of Science databases. We included studies that evaluated the diagnostic performance of NIRS in detecting intracranial hematoma in both adult and pediatric patients suspected of TBI in prehospital or emergency settings, using brain computed tomography (CT) scan or magnetic resonance imaging as the gold standard. **Results:** Eighteen studies enrolling 2979 patients were included. NIRS exhibited an Area Under the Curve (AUC) of 0.91 (95% confidence interval [CI]: 0.88, 0.93), with a sensitivity of 0.86 (95% CI: 0.78, 0.91), and specificity of 0.82 (95% CI: 0.72, 0.89) across all age groups. In children, the results demonstrated an AUC of 0.92 (95% CI: 0.89, 0.94), sensitivity of 0.95 (95% CI: 0.21, 1.00), and specificity of 0.81 (95% CI: 0.65, 0.91). Among adults, the AUC was 0.91 (95% CI: 0.88, 0.93), with sensitivity and specificity of 0.86 (95% CI: 0.78, 0.92) and 0.83 (95% CI: 0.70, 0.91), respectively. Performance improved when NIRS was operated by non-physicians (AUC = 0.94 [95% CI: 0.91, 0.96], sensitivity = 0.90 [95% CI: 0.79, 0.95], specificity = 0.85 [95% CI: 0.71, 0.93]) compared to physicians (AUC = 0.90 [95% CI: 0.87, 0.92], sensitivity = 0.88 [95% CI: 0.77, 0.94], specificity = 0.75 [95% CI: 0.59, 0.76]). Patients' age group and operator type were identified as potential sources of heterogeneity. Sensitivity analyses confirmed the robustness of the findings, particularly in mild TBI cases and studies implementing a OD > 0.2 as the threshold for a positive NIRS result. **Conclusion:** NIRS proves to be an effective diagnostic tool for detecting traumatic intracranial hematoma in both pediatric and adult groups, with high sensitivity and specificity. Its utility in prehospital triage, operated by physicians or paramedics, underscores its potential for broader clinical application.

Keywords: Spectroscopy, near-infrared; Intracranial hemorrhages; Intracranial hemorrhage, traumatic; Hematoma, subdural, intracranial; Brain injuries, traumatic

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1. Introduction

Traumatic Brain Injury (TBI) is a global health burden and remains one of the most significant causes of mortality and morbidity among people of all ages worldwide (1). The incidence of TBI is on the rise globally and is reported to be approximately 939 cases per 100,000 and there are nearly 69 million cases diagnosed with TBI every year. Intracranial hematoma is the leading cause of mortality and disability after severe TBI (2). Evaluating patients suspected of TBI involves a thorough physical examination, determining the severity of injuries, assessing consciousness levels using the Glasgow Coma Scale (GCS), and evaluating the risk of intracranial hemorrhage (ICH), a frequent severe complication. Early and precise detection of such conditions is particularly vital in the prehospital stage, where initial identification of intracranial injuries can significantly influence the success of subsequent management. Although brain computed tomography (CT) scan without contrast remains the gold standard for diagnosing ICH in TBI (3), it is limited by availability in prehospital and resource-constrained settings, cost, and radiation exposure.

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Near-Infrared Spectroscopy (NIRS) has recently been investigated for its potential to provide rapid, safe, and effective diagnosis without the need for complex equipment or exposing patients to radiation (4-6). NIRS works by the transmission of near-infrared light through cranial structures to a certain depth. This technology utilizes the distinct absorption properties of chromophores within the skull, primarily oxyhemoglobin and deoxyhemoglobin, which absorb near-infrared light mainly at wavelengths ranging from 700 to 1000 nm (7). As NIRS measures the differential absorption across various cranial areas, it allows for the detection and monitoring of intracranial physiological and pathological changes. The method excels in identifying areas where extravascular blood, which has a higher concentration of hemoglobin due to hemorrhage, absorbs more near-infrared light compared to normal tissue (8). This capability makes NIRS an effective tool for detecting ICH.

Furthermore, NIRS can be performed quickly, does not require extensive technical training, and is safe for both patients and healthcare providers since it involves no radiation exposure (9). These features potentially make NIRS a valuable diagnostic tool, particularly in settings where CT scans are unavailable.

There is currently inconclusive evidence to support the clinical applicability of NIRS in intracranial hematoma detection and patients' triage at the prehospital or low-facility settings when CT is not accessible. This systematic review and meta-analysis aimed to gather all current evidence and determine the diagnostic yield of NIRS for detecting intracranial hematoma in TBI patients.

2. Methods

2.1. Study design and setting

The present systematic review and meta-analysis was designed and conducted adhering to the preferred reporting items for systematic review and meta-analysis of diagnostic test accuracy studies (PRISMA-DTA) (10). Although the study protocol has not been previously registered or published, our approach aligns with rigorous standards.

This study aimed to comprehensively examine the diagnostic value of NIRS for detecting intracranial injury among adult and pediatric patients with suspected TBI. The study protocol defines the population (P), index test (I), and target condition (T) as follows: P: Adult and pediatric patients with suspected TBI. I: Performing NIRS in a prehospital or ED setting. T: Presence of intracranial hematoma confirmed by brain CT scan or magnetic resonance imaging (MRI).

2.2. Search strategy

The search strategy involved selecting relevant keywords from existing literature, exploring MeSH and Emtree terms, and consulting field experts. Online databases, including Medline (via PubMed), Embase, Scopus, and Web of Science, were searched until July 13th, 2024, using the identified keywords, standard tags, and Boolean operators. Additionally, manual searches were conducted on Google, Google Scholar, as well as forward and backward citation tracking of included studies. No restrictions were imposed on language or publication date.

We intended to translate articles in languages other than English using online services such as Doc Translator, and then have them reviewed by an expert translator fluent in both the original language and English to ensure accuracy. However, all of the relevant studies retrieved were written in English. Appendix 1 provides the search queries used across all explored databases.

2.3. Selection criteria

The inclusion criteria encompassed observational studies assessing the performance of NIRS in detecting intracranial hematoma among patients with suspected TBI. Exclusion criteria included studies using reference standards other than CT or MRI, prognostic studies, lack of reporting sufficient data for meta-analysis of diagnostic accuracy studies. Additionally, animal studies, studies not assessing our outcome, non-traumatic brain injuries, abstracts, review articles, and studies not reporting the required data were excluded.

2.4. Screening and data collection

Records obtained from systematic and manual searches were imported into Endnote version X9.0 software (Clarivate Analytics, Philadelphia, PA, USA), with duplicates removed. Two independent reviewers screened titles and abstracts, retrieving full texts of potentially relevant articles. Eligible articles were selected based on established inclusion and exclusion criteria for entry into the meta-analysis. Two independent reviewers assessed full-text articles and recorded relevant data using a pre-designed checklist. Disagreements between reviewers were resolved through discussion and consultation with a third author.

Data extracted included study characteristics (author, publication year, country), study design, sample size, mean age, male number, patient settings, TBI severity, identification of TBI on admission imaging, NIRS operator, NIRS device model, NIRS cutoff, interval of trauma and conduction of spectroscopy, reference standard, interval of spectroscopy and first imaging study, interval of trauma and first imaging, patients' age group, and diagnostic performance indicators (sensitivity, specificity, false/true positives/negatives). In cases where sensitivity or specificity data were unavailable, a cross table was constructed using the results of both the index test and reference standard, enabling manual calculation of necessary diagnostic values.

2.5. Quality assessment and certainty of the evidence

The risk of bias in included studies was assessed using the Quality Assessment of Diagnostic Accuracy Studies version 2

(QUADAS-2) tool (11).

Two reviewers independently evaluated studies based on QUADAS-2 guidelines, which assess risk of bias and applicability across domains including patient selection, index test, reference standard, and flow and timing. Disagreements were resolved through discussion or consultation with a third reviewer.

The level of evidence was determined using the Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) framework (12). Each outcome's level of evidence was assessed by considering risk of bias, imprecision, inconsistency, indirectness, and publication bias, as outlined in the GRADE framework.

2.6. Statistical analysis

We utilized STATA 17.0 (StataCorp LLC, College Station, TX, USA) to conduct the analyses. Given the anticipated methodological and clinical heterogeneity, we applied a random-effects model. The "midas" package was employed to compute the area under the receiver operating characteristic curve (AUC), sensitivity, specificity, positive likelihood ratio (PLR), negative likelihood ratio (NLR), diagnostic odds ratio (DOR), and diagnostic score with their corresponding 95% confidence intervals (CIs). Summary receiver operating characteristic (SROC) curves were constructed for the discriminative ability of NIRS in detecting intracranial hematoma. Statistical heterogeneity was assessed using the I^2 statistic and the chi-squared test, with $p<0.1$ or $I^2>50\%$ indicating significant heterogeneity. Publication bias was evaluated using Deek's asymmetry funnel plot.

Subgroup analyses were conducted based on age group (adults vs pediatrics) and NIRS operator (physician vs non-physician). Furthermore, sensitivity analyses were performed on mild TBI patients, from studies using the predefined cutoff of OD>0.2 as positive index test, as well as those utilizing the Infrascanner2000 (Infrascan Inc., Philadelphia, USA), to explore the impact of those variables on the effect sizes.

3. Results

3.1. Study selection

A systematic search across four electronic databases yielded 5552 records. After removing duplicates, 2679 articles' titles and abstracts were screened, and the full text of 123 documents was reviewed. Forward and backward citation tracking of included studies, as well as searches on Google and Google Scholar, yielded three additional eligible articles based on our inclusion and exclusion criteria. Among the evaluated studies, one utilized doppler ultrasonography as the reference standard (13) and one assessed the prognostic value of NIRS (14). Also, studies were excluded for lack of sufficient data for quantitative synthesis, animal studies, no desired outcomes, non-traumatic brain injury, abstracts, review studies, and not reporting the required data (Figure 1). Ultimately, data from 18 papers were extracted and included in the analysis (4-8, 15-27).

All included studies were prospective cohort or cross-sectional studies with the design suitable for diagnostic accuracy, which recruited patients with suspected head injuries in ED or pre-hospital settings. There were five studies on pediatrics and 14 on adults. Three studies included mild TBI (GCS 13-15) patients, one mild to moderate (GCS 9-15), one moderate to severe (GCS 3-12), and the rest either included all severities nor not reported the GCS of patients. Studies utilized two different definitions of hematoma as positive reference standard; 12 used any size hematoma, 3 used hematoma volume >3.5 ml and depth <2.5 cm (<3.5 cm in one study), and 3 studies reported data for both definitions. In the latter case, we utilized data of any size hematoma for meta-analysis. Among the included studies, 10 utilized Infrascanner 2000 (Infrascan Inc., Philadelphia, USA) as the index test. Based on delta optical density (OD) between two symmetric points of skull, fifteen studies had utilized predefined criteria (OD>0.2 or OD>0.45) for positive index test. The operators who performed scanning with NIRS were physicians in 7 and paramedics, technicians or trained non-physician staff in 7 studies. Summary characteristics of the included studies are presented in Table 1.

3.2. Risk of bias assessment

Based on our assessment of the quality of included studies using the QUADAS-2 tool, four studies were rated as low risk, while fourteen raised some concerns. Studies with potential risk of bias had limitations related to the sampling process (non-random or non-consecutive sampling), not using predefined cutoff points of OD, lack of statement that CT scan results were interpreted without the knowledge of the results of NIRS, and not utilizing the same reference standard for all patients (Table 2).

3.3. Diagnostic value of NIRS in detecting intracranial hematoma

Eighteen studies assessed the diagnostic performance of NIRS for detecting intracranial hematoma, enrolling a total of 2979 patients with suspected TBI, among whom 825 (28%) were diagnosed with intracranial hematoma in the first admission imaging. Pooled analysis showed an AUC of 0.91 (95% CI: 0.88, 0.93; Figure 2), sensitivity of 0.86 (95% CI: 0.78, 0.91), and specificity of 0.82 (95% CI: 0.72, 0.89) (Figure 3). PLR and NLR were 4.8 (95% CI: 2.9, 8.0) and 0.17 (95% CI: 0.11, 0.28), respectively (Figure 4). Diagnostic score and DOR were 3.34 (95% CI: 2.47, 4.20) and 28 (95% CI: 12, 67), respectively (Figure 5). There was considerable heterogeneity among the studies (I^2 = 97% [95% CI: 95, 99]). No evidence of publication bias was detected in the analyzed studies (p = 0.681; Figure 6).

3.4. Subgroup analysis

Pooled data analysis from 5 studies on 653 children with suspected TBI demonstrated the AUC of 0.92 (95% CI: 0.89, 0.94), sensitivity of 0.95 (95% CI: 0.21, 1.00), and specificity of 0.81 (95% CI: 0.65, 0.91) in detecting intracranial hematoma (I^2 = 0.0%) (Table 3). AUC, sensitivity, and specificity for adults were 0.91 (95% CI: 0.88, 0.93), 0.86 (95% CI: 0.78, 0.92), and 0.83 (95% CI: 0.70, 0.91), respectively. The patients' age group was a potential source of heterogeneity since data of pediatric population was homogenous. NIRS demonstrated higher performance when done by non-physicians (AUC = 0.94 [95% CI: 0.91, 0.96], sensitivity = 0.90 [95% CI: 79, 0.95], specificity = 0.85 [95% CI: 0.71, 0.93]) compared to physicians (AUC = 0.90 [95% CI: 0.87, 0.92], sensitivity = 0.88 [95% CI: 0.77, 0.94], specificity = 0.75 [95% CI: 0.59, 0.76]; I^2 = 0.0%) (Table 3). The NIRS operator was also another potential source of heterogeneity.

3.5. Sensitivity analysis

Sensitivity analysis on mild TBI patients resulted in an AUC of 0.97 (95% CI: 0.95, 0.98) sensitivity of 0.97 (95% CI: 0.73, 1.00) and specificity of 0.79 (95% CI: 0.54, 0.93). Another sensitivity analysis on studies with a predefined cutoff of OD>0.2 for assuming positive NIRS, resulted in an AUC of 0.92 (95% CI: 0.89, 0.94), sensitivity of 0.87 (95% CI: 0.76, 0.93), and specificity of 0.83 (95% CI: 0.71, 0.91). Another sensitivity analysis on 12 studies that utilized the Infrascanner2000 (Infrascan Inc., Philadelphia, USA), yielded an AUC of 0.91 (95% CI: 0.88, 0.93), sensitivity of 0.89 (95% CI: 0.80, 0.94), and specificity of 0.77 (95% CI: 0.62, 0.87).

3.6. Certainty of evidence

The level of evidence regarding the diagnostic performance of NIRS for detecting intracranial hematoma was downgraded due to potential concerns about the risk of bias and was scored as moderate. Although there was substantial heterogeneity among the studies, we identified some potential sources for it and thus did not downgrade for inconsistency (Table 4).

4. Discussion

NIRS is a useful tool for detecting the traumatic intracranial hematoma in both pediatric and adult groups. High sensitivity and specificity are observed when physicians as well as paramedics utilize NIRS device, therefore it can be considered an efficient tool in prehospital triage.

However, this prehospital tool is more precise when detecting large, unilateral, superficially located hematoma lesions, and cannot be considered as a replacement for brain CT-scan. NIRS can also be a useful tool in triage of TBI patients with limited time available, in overcrowded emergency rooms, as well as decision making for situations when transporting the trauma patients to a center with neurosurgical equipment is considered. In addition, NIRS is a valuable device to perform the initial screening of TBI patients in the centers that CT scan or MRI is not available.

In this systematic review and meta-analysis, we assessed the diagnostic accuracy of NIRS in detection of intracranial hematoma in TBI patients. This systematic review and meta-analysis show that NIRS could be useful as a supplementary decision tool for screening patients with head injury. Meta-analysis resulted in a high sensitivity and specificity of NIRS in detecting intracranial hematoma. Also, the results demonstrated no superiority of diagnostic performance when the operator was a physician; therefore, NIRS could be used by paramedics or trained technicians in a prehospital environment (5, 7, 19, 25). NIRS can be considered a fast, non-invasive, simple, and portable device that is carefully placed on the scalp and allows for reliable detection of intracranial hemorrhage (23, 24). This screening tool was first utilized more than forty years ago by F.F Jobsis for monitoring cerebral tissue oxygenation. NIRS is based on reflection of non-ionizing and safe light with a wavelength of 700 to 1000 nm that passes through scalp, skin, and tissue, making it appropriate for use in radiation-sensitive groups (28).

In a systematic review conducted by Viderman et al., the sensitivity and specificity of NIRS for detecting intracranial hemorrhage were reported to be 90% and 77%, respectively (no CI obtained). The sensitivity of NIRS is slightly higher than that computed in this study. Also, the specificity of NIRS was assessed to be lower by 6%. This controversy could originate from two key differences. First, no meta-analysis was performed in the aforementioned study, and the pooled estimation was not based on robust methodology. Additionally, the number of included papers in that study is half that of our study, as the search was only conducted in PubMed and Google Scholar. Another meta-analysis published in 2017, demonstrated a sensitivity of 78% and specificity of 90% by pooled data analysis from 6 out of the 18 studies included in our meta-analysis (7, 28). This demonstrates the importance of applying NIRS in various clinical settings to reveal the potential factors impacting the diagnostic accuracy of the device.

The higher sensitivity of the device in the pediatric population can be explained by the fact that children have thinner scalps, which can lead to more NIRS signal detection and less noise alteration (29). However, further research is required to confirm the results, as there are only three studies on the pediatric population with TBI. Besides the patients' age group, the specialty of the operator (either physicians or nurses/paramedics) was considered as another potential source of heterogeneity.

NIRS is a useful device, which makes rapid identification of intracranial hematoma in TBI patients easier and can be used for prehospital screening (28, 29). This advantage could also aid in diagnosis of TBI patients in medical centers in which no CT- scan is available. Moreover, prehospital triage of TBI patients could potentially result in a more accurate transportation of the patients, especially when a

craniotomy-equipped specialized hospital is favored. Our study highlighted the acceptable diagnostic accuracy of NIRS as a screening tool for detecting intracranial hemorrhage, but the efficacy of applying this tool in improving the patients' outcomes remains undetected. The study of Schober et al. evaluated the feasibility of NIRS for detection of intracranial hematoma in the helicopter emergency medical service (HEMS) setting (20, 30). This study showed some drawbacks of NIRS within the HEMS setting. Applying NIRS on healthy volunteers showed a significant occurrence of false positives when the scanning results was taken by the first attempt. Consequently, this approach was considered ineffective as it actually required more time-consuming repeated measurements. The high false positive rate in the study could be originated from the type of device as well. This is one important confounder and no published studies are available to directly compare the diagnostic accuracy between different portable NIRS devices.

Despite the advantages of the NIRS method for identifying intracranial hematomas and acceptable diagnostic accuracy results mentioned above, there are several limitations for this device. The size and depth of intracranial hemorrhage from the brain surface seem to be major factors affecting sensitivity and specificity of NIRS. There are limitations for NIRS device for identifying traumatic intracranial hemorrhage lesions smaller than 3.5 mm within a depth of more than 2.5 cm. On the other hand, the portable NIRS cannot determine the precise size and exact location of hematoma (6, 21, 31). The utility of NIRS in identifying symmetrical bilateral abnormalities is limited. In addition, near-infrared technology cannot reliably identify chronic subcutaneous hematoma. Therefore, this triage tool is more useful for detecting large, unilateral, superficial hematoma lesions (16, 17, 29). It is worth mentioning that, studies have stated that skin pigmentation and hair type can potentially affect the accuracy of the NIRS. The possible explanation can be altering the pathway of penetration of the non-ionizing light in presence of darker skin or thick hair (21, 23, 28).

5. Limitations

This study has certain limitations that should be acknowledged. Firstly, there was significant heterogeneity across the included studies, which we aimed to address the potential sources through sub-group analyses based on age groups and NIRS operators. However, limited data availability hindered further subgroup analyses based on factors such as TBI severity, hematoma types, or the timing of NIRS assessment in relation to injury. Secondly, the QUADAS-2 risk of bias assessment tool identified concerns regarding potential biases in multiple domains, including patient selection, index test application, reference standard implementation, or study flow and timing, across the majority of the included studies.

6. Conclusion

This systematic review and meta-analysis demonstrated the promising diagnostic utility of NIRS for detecting intracranial hematoma in patients with TBI. Across multiple studies, NIRS exhibited high diagnostic accuracy, with consistent performance noted in both adult and pediatric populations. The technique was proved to be particularly well in cases of mild TBI and when operated by non-physician personnel, underscoring its potential for broader implementation in prehospital and resource-limited settings. While not intended as a replacement for CT scan or MRI, NIRS can serve as an effective triage tool to identify patients requiring urgent neuroimaging and neurosurgical intervention. However, future research should explore strategies to enhance NIRS capabilities and evaluate its real-world impact on clinical decision-making.

7. Declarations

7.1. Acknowledgments

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7.2. Data availability statement

The dataset generated and analyzed during the current study is available from the corresponding author upon reasonable request.

7.3. Competing interests

The authors declare no competing interests.

7.4. Funding

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7.5. Using artificial intelligence

None.

7.6. Author contributions

Study design: HZ, AT, SP
Data gathering: AZ, MJ, NS, MY, MM, SSA, AS, MB, NB, AG, MA, AA
Analysis: HZ, NS, MY, MM, SSA, AS
Interpretation: HZ, AZ, MJ, NS, MY, SP
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Reading and approving the final manuscript: All authors

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Table 1: Characteristics of the included studies

Author	Sample size, mean age (yrs), male number	TBI severity	Definition of hematoma in imaging	Interval of trauma to NIRS	NIRS Operator	NIRS device	OD cutoff for positive scan	Reference standard	Age group
Akyol, 2016, Turkey	151, 49.9, 77	Mild	Any size hematoma	NR	ED physicians	Infrascanner	NR	CT scan	Adult
Bressan, 2013, Germany	103, NR, 57	Mild	Any size hematoma	<12hr	Physicians	Infrascanner model 1000	OD> 0.2	CT scan	Pediatric
Coskun, 2010, Turkey	92, NR, NR	NR	Any size hematoma	NR	Paramedics	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	OD> 0.2	CT scan	Adult
Coskun, 2010, Turkey	161, NR, NR	NR	Any size hematoma	NR	Paramedics	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	OD> 0.2	CT scan	Pediatric
Esmaeili, 2022, Iran	300, 39.4, 255	Mild To Moderate	Any size hematoma	< 12hr	Technicians	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	OD> 0.2	CT scan	Adult
Francis, 2005, India	64, NR, NR	NR	Any size hematoma	NR	NR	NR (760 nm)	Not predefined	CT scan	Adult
Ghalenoui, 2008, Iran	148, 36.8, 94	NR	Any size hematoma	NR	Physicians	CrainScan, BYTEC, Germany.	OD >0.45	CT scan	Adult
Gramer, 2023, Uganda	500, 55.4, 289	All severities	Any size hematoma	NR	NR	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	OD> 0.2	CT scan	Adult
Kessel, 2007, Israel	110, 56.2, 64	All severities	Any size hematoma	NR	Trained staff	CrainScan, BYTEC, Germany	OD >0.45	CT scan	Adult
Kirschen, 2021, USA	344, 9.5, 225	All severities	All hematomas	NR	Research coordinators and assistants	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	OD> 0.2	CT scan	Pediatric
Kontojannis, 2019, UK	205, 48.3, 160	All severities	Any size hematoma	NR	Trained neurosurgeons	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	OD> 0.2	CT scan	Adult
Leon-Carrion, 2010, Spain	35, 47.6, 29	All severities	Any size hematoma	NR	Trained hospital personnel,	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	OD> 0.2	CT scan	Adult
Liang, 2016, China	102, 41.0, 58	All severities	Hematoma vol > 3.5 ml and depth < 2.5 cm	NR	Trained operators	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	OD> 0.2	CT scan	Adult
Peters, 2017, Netherlands	22, 56.3, 13	All severities	Any size hematoma	< 24hr	HEMS physicians	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	Not predefined	CT scan	Adult
Peters, 2017, Netherlands	3, 9.3, 2	Moderate To Severe	Any size hematoma	< 12hr	HEMS physicians	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	not predefined	CT scan	Pediatric
Robertson, 2010, USA and India	365, 36.7, 273	All severities	Any size hematoma	NR	Trained operators	NR (808 nm)	OD> 0.2	CT scan	Adult
Semenova, 2016, Russia	42, 9.1, 26	Mild	Any size hematoma	NR	Neurosurgeon	Infrascanner model 1000	DOD > 0.2	CT scan	Pediatric
Trehan, 2017, India	100, NR, 69	All severities	Any size hematoma	NR	NR	CrainScan, BYTEC, Germany	OD >0.45	CT scan	Adult
Xu, 2017, China	85, 48.3, NR	All severities	Hematoma vol > 3.5 ml and depth < 2.5 cm	NR	Trained operators	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	OD> 0.2	CT scan / MRI	Adult
Yuksen, 2020, Thailand	47, 70.3, 21	Mild	Hematoma vol > 3.5 ml and depth < 3.5 cm	<72hr	Trained emergency physician	Infrascanner2000 (Infrascan Inc., Philadelphia, USA)	Not predefined	CT scan	Adult

Yrs: years; TBI: traumatic brain injury; NR: not reported; vol: volume; NIRS: near infrared spectroscopy; HEMS: helicopter Emergency Medical Service; OD: delta optical density; CT scan: computed tomography scan; hr: hours; ED: emergency department.

Table 2: Risk of bias assessment of the included studies based on the QUADAS-2 tool

Study	Risk of bias				Applicability			Overall
	Patients' selection	Index test	Reference standard	Flow and timing	Patients' selection	Index test	Reference standard	
Akyol, 2016	Low	Low	Low	Low	Low	Low	Low	Low
Bressan, 2013	High	Low	Low	High	Low	Low	Low	Some Concern
Coskun, 2010	Unclear	Low	Low	Low	Low	Low	Low	Some Concern
Esmaeili, 2022	Unclear	Low	Low	Low	Low	Low	Low	Some Concern
Francis, 2005	High	High	Low	Unclear	Low	Low	Low	Some Concern
Ghalenoui, 2008	Low	Low	Low	Low	Low	Low	Low	Low
Gramer, 2023	Low	Low	Low	Low	Low	Low	Low	Low
Kessel, 2007	High	Low	Low	Low	Low	Low	Low	Some Concern
Kirschen, 2021	High	Low	Low	High	Low	Low	Low	Some Concern
Kontojannis, 2019	Low	Low	Low	Low	Low	Low	Low	Low
Leon-Carrion, 2010	Unclear	Low	Low	Low	Low	Low	Low	Some Concern
Liang, 2016	High	Low	Low	Low	Low	Low	Low	Some Concern
Peters, 2017	Low	High	Low	Low	Low	Low	Low	Some Concern
Robertson, 2010	Unclear	Low	Low	Low	Low	Low	Low	Some Concern
Semenova, 2016	High	High	Unclear	Unclear	Low	Low	Low	Some Concern
Trehan, 2017	Unclear	Low	Low	Low	Low	Low	Low	Some Concern
Xu, 2017	High	Low	Low	High	Low	Low	Low	Some Concern
Yuksen, 2020	Unclear	High	Low	Low	Low	Low	Low	Some Concern

High: high risk of bias; Low: low risk of bias; Unclear: unclear risk of bias.

Table 3: Subgroup analysis of the diagnostic performance of NIRS for detecting intracranial hematomas in patients with suspected TBI

Subgroup	Observations (N)	AUC (95% CI)	Sensitivity (95% CI)	Specificity (95% CI)	PLR (95% CI)	NLR (95% CI)	DOR (95% CI)	I^2
Age group								
Adult	15	0.91 (0.88-0.93)	0.86 (0.78, 0.92)	0.83 (0.70, 0.91)	5.0 (2.7-9.4)	0.17 (0.10-0.27)	30 (11-81)	97%
Pediatric	5	0.92 (0.89-0.94)	0.95 (0.21, 1.00)	0.81 (0.65, 0.91)	5.1 (2.3-11.5)	0.06 (0.00-3.89)	79 (1-8618)	0%
NIRS Operator								
Physicians	8	0.90 (0.87-0.92)	0.88 (0.77, 0.94)	0.75 (0.59, 0.86)	3.5 (1.9-6.3)	0.16 (0.07-0.36)	21 (6-82)	0%
Non-physicians	8	0.94 (0.91-0.96)	0.90 (0.79, 0.95)	0.85 (0.71, 0.93)	6.0 (3.0-12.0)	0.12 (0.06-0.26)	49 (16-152)	95%

NIRS: near-infrared spectroscopy; TBI: traumatic brain injury; CI: Confidence interval; AUC: Area under the curve; DOR: Diagnostic odds ratio; NLR: Negative likelihood ratio; PLR: Positive likelihood ratio.

Table 4: Certainty of the evidence based on the GRADE framework

Outcome	Sample size	Risk of bias	Imprecision	Inconsistency (I^2)	Indirectness	Publication bias	Level of evidence*
Intracranial hematoma	2979	Some concern	Not present	Not present	Not present	Not present	Moderate

GRADE: Grading of Recommendations, Assessment, Development, and Evaluations.

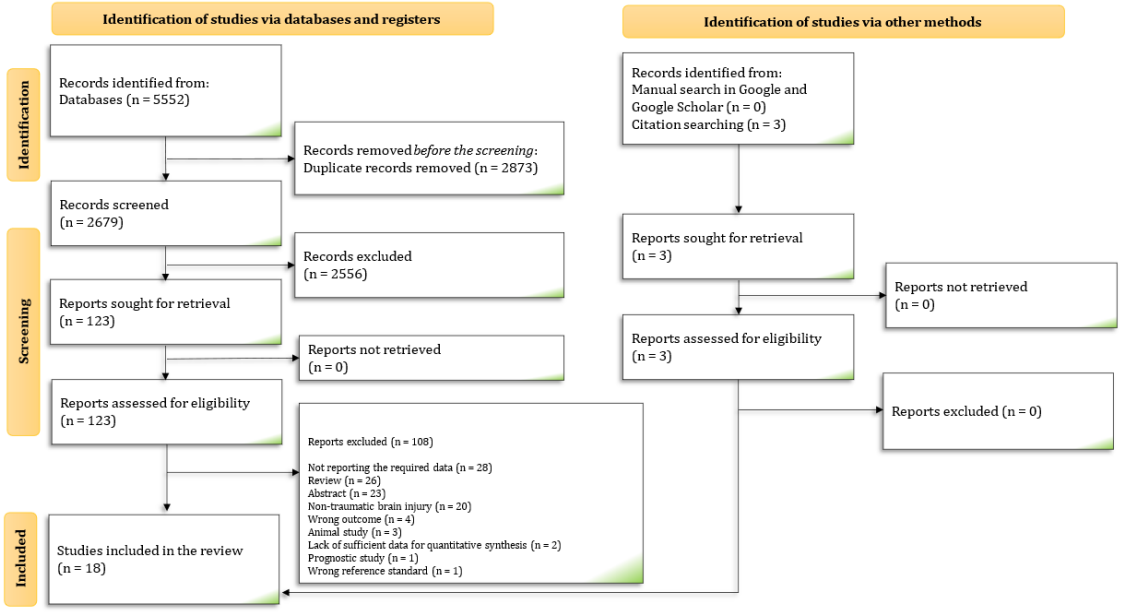

Figure 1: The PRISMA flow diagram depicts the flow of the study selection process through the different phases of the present systematic review. PRISMA: preferred reporting items for systematic review and meta-analysis.

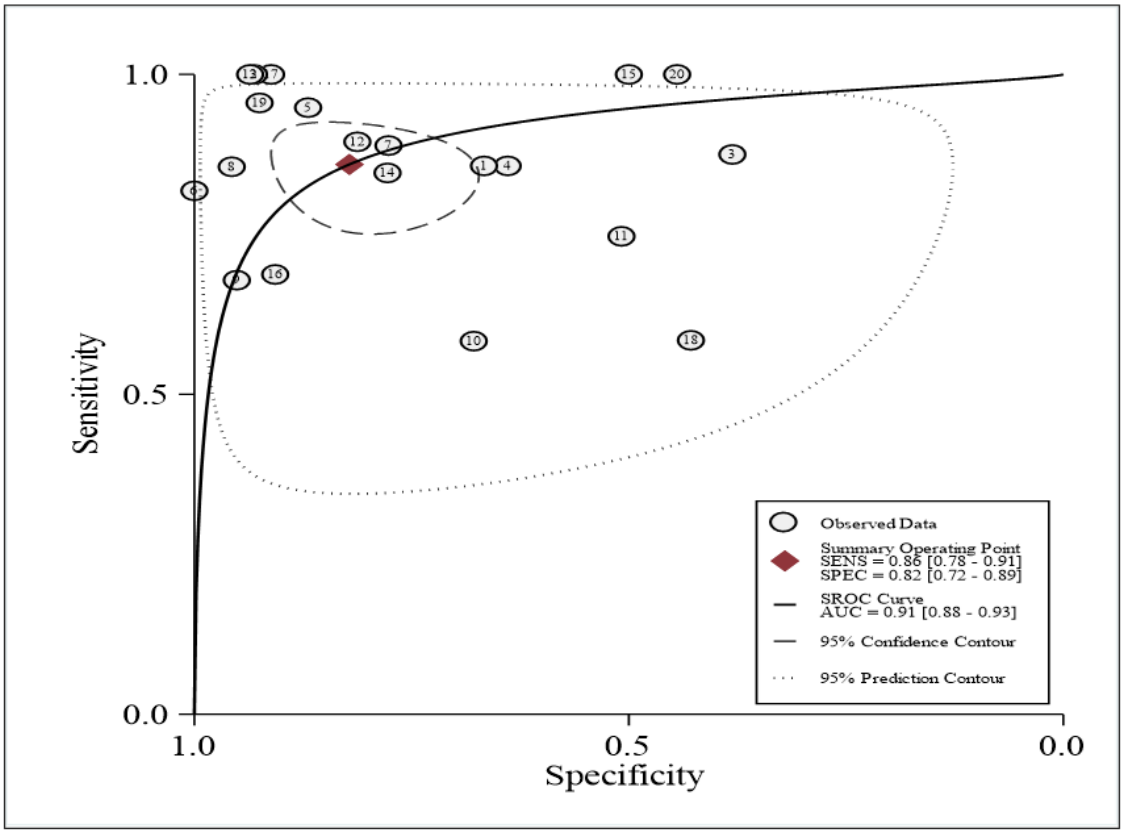

Figure 2: Summary Receiver Operating Characteristic Curve of near-infrared spectroscopy (NIRS) in detecting intracranial hematoma; SENS: sensitivity; SPEC: specificity; AUC: area under the curve.

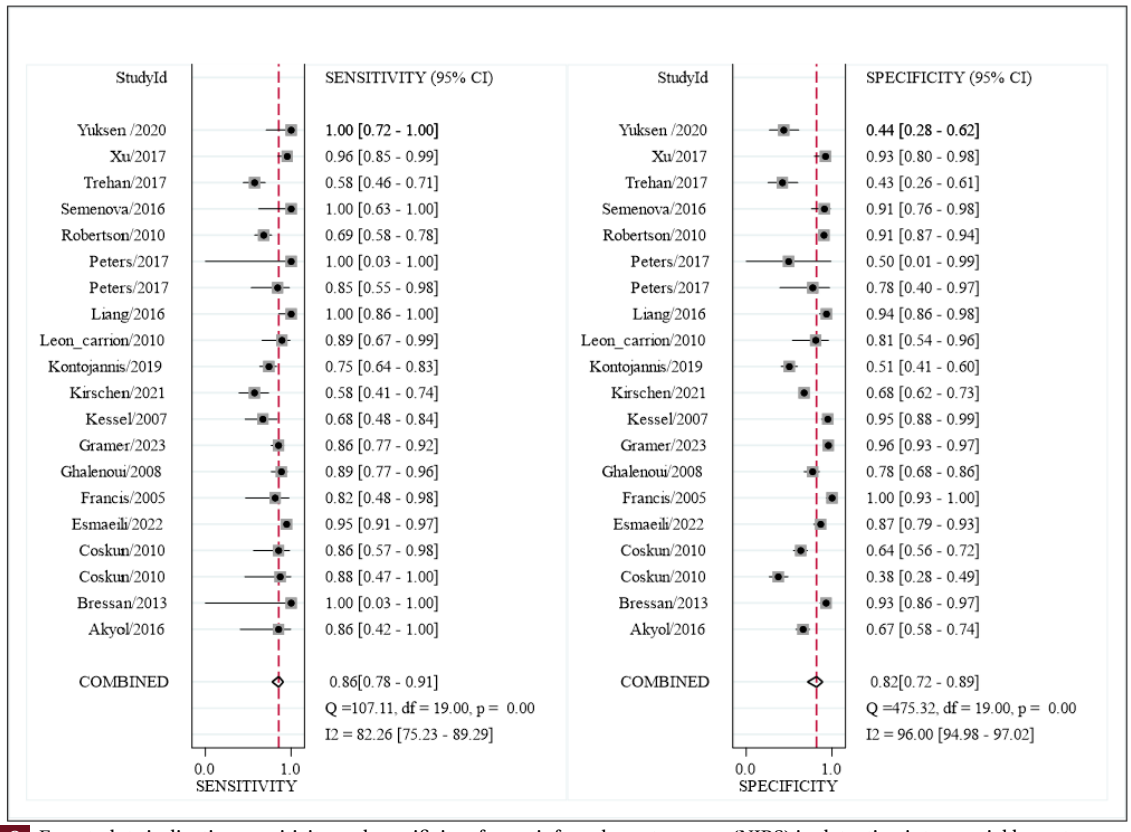

Figure 3: Forest plots indicating sensitivity and specificity of near-infrared spectroscopy (NIRS) in detecting intracranial hematoma.

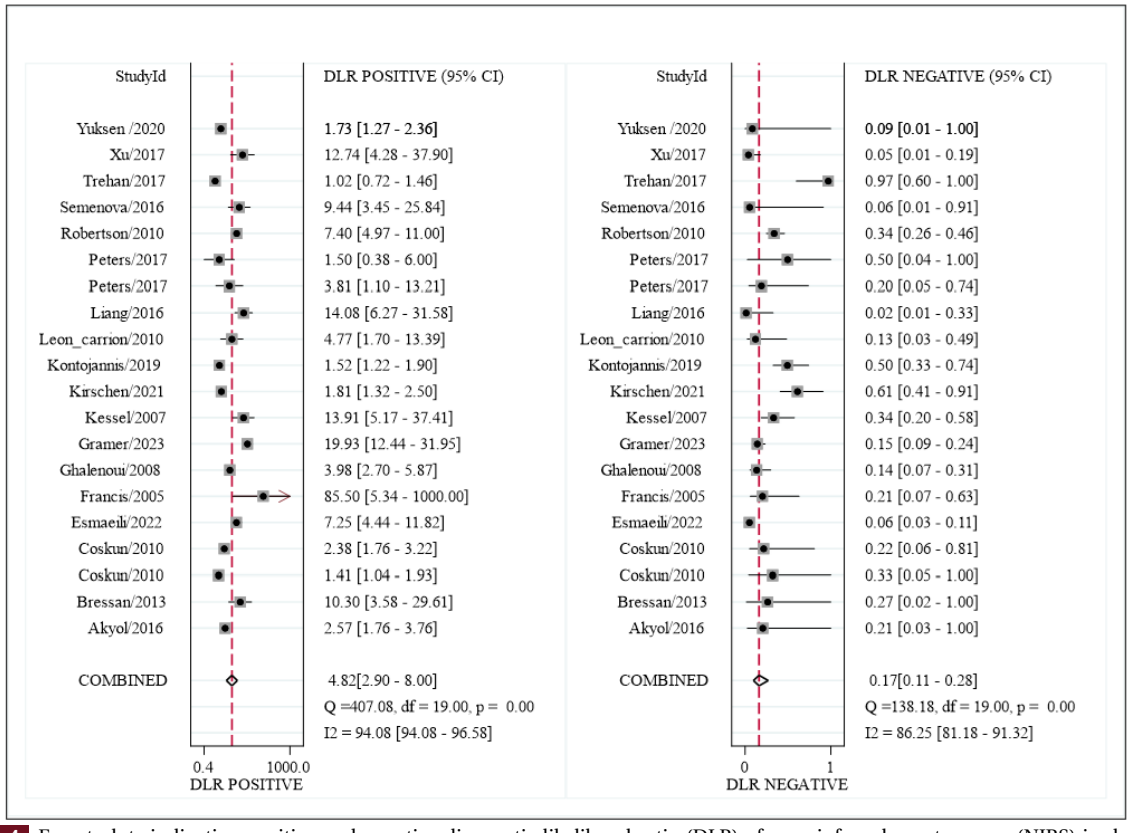

Figure 4: Forest plots indicating positive and negative diagnostic likelihood ratio (DLR) of near-infrared spectroscopy (NIRS) in detecting intracranial hematoma.

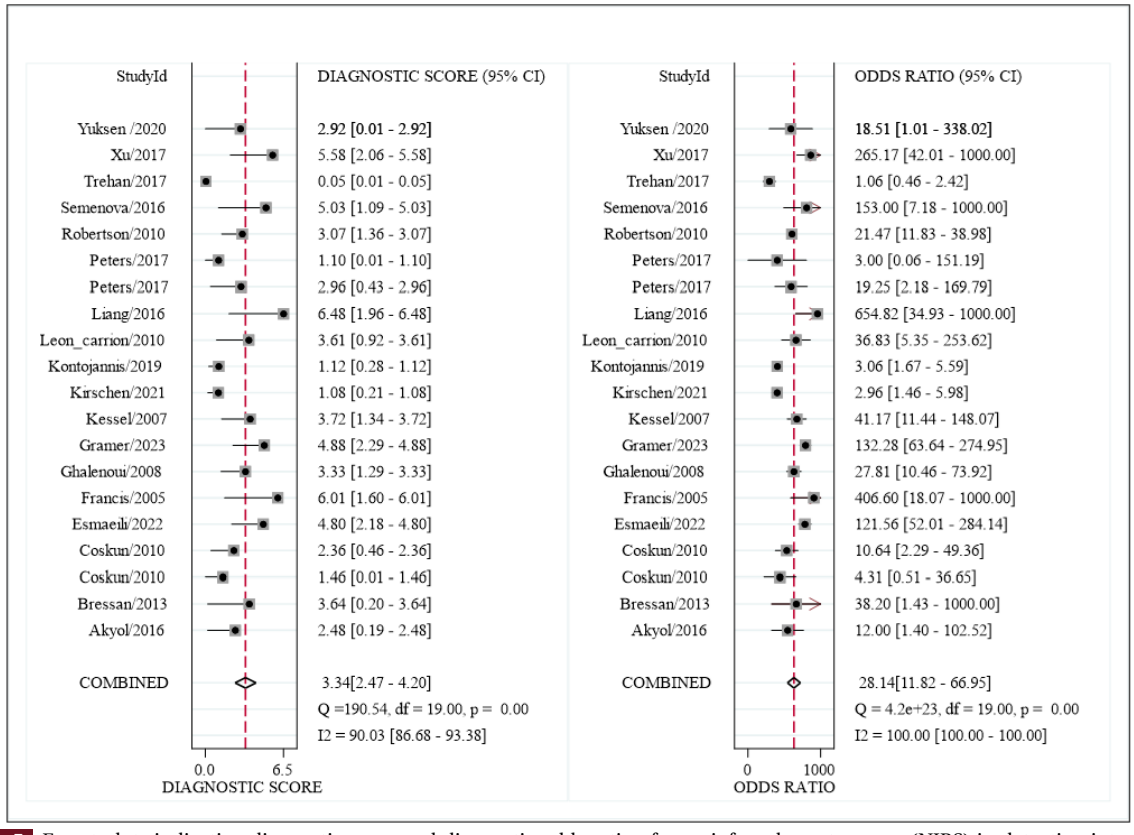

Figure 5: Forest plots indicating diagnostic score and diagnostic odds ratio of near-infrared spectroscopy (NIRS) in detecting intracranial hematoma.

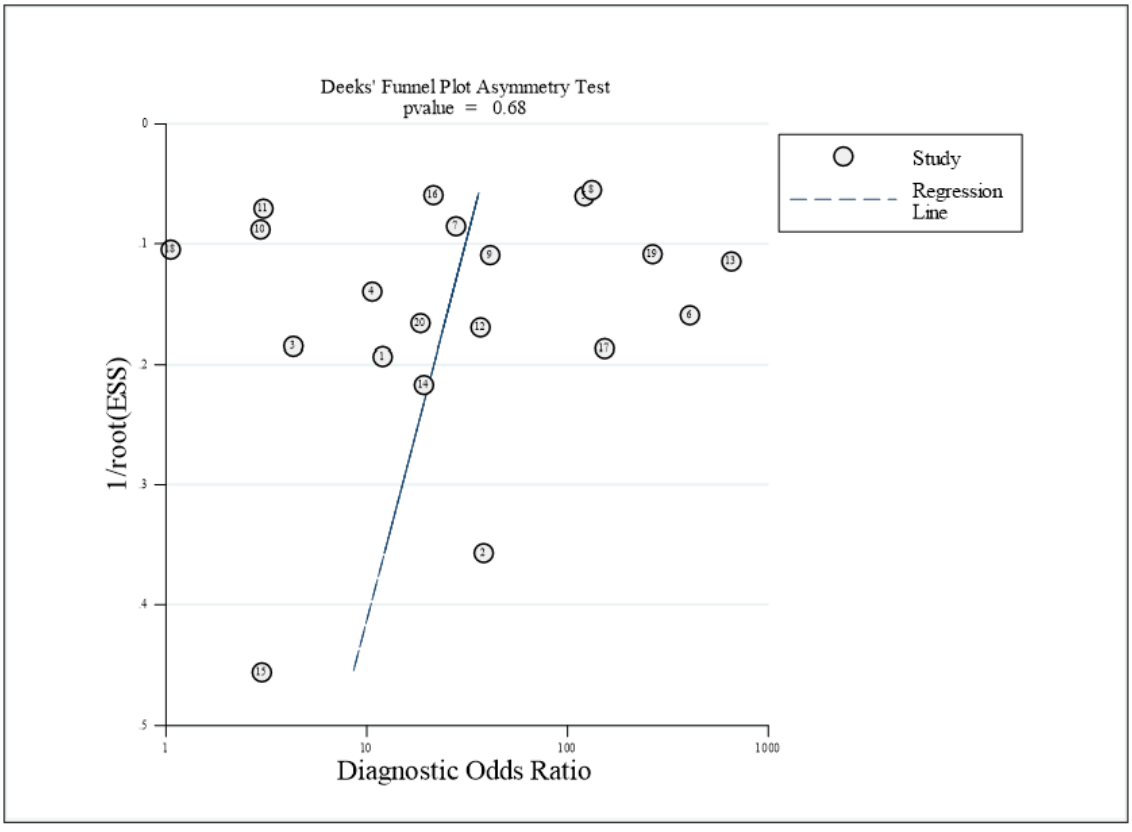

Figure 6: Deeks' Funnel plot asymmetry tests indicate no evidence of publication bias for diagnostic yield of near-infrared spectroscopy (NIRS) in detecting intracranial hematoma.